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Title: Basic Radiation and Criticality

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Basic Radiation and Criticality

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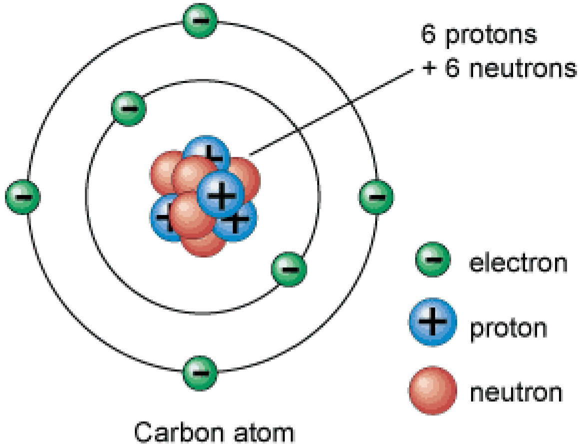
Introduction

- Radiation is all around us, within us, and often misunderstood by many
- We will discuss the origins and types of radiation, units of measurements, effects on the human body
- We will also discuss the concept of criticality, which is a key topic for nuclear reactors, weapons, and accidents

Elements, Nuclides, and Isotopes



Constituents of the Atom: Protons, Neutrons, and Electrons

Elements: Defined by the number of protons in the nucleus

Isotopes: atoms from same element but with different number of neutrons

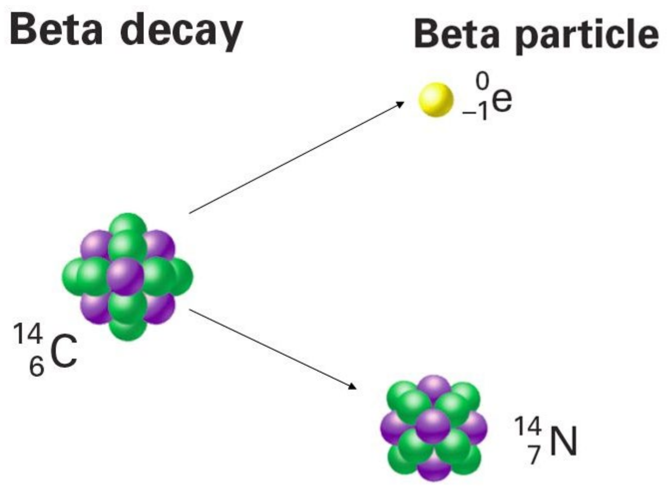
Nuclides (or Radionuclides): a more general term specifying element and atomic mass

^{12}C (Carbon-12):

a) has 6 protons and 6 neutrons
b) Atomic number (Z): # of protons
c) Atomic Mass (A): # of protons + neutrons

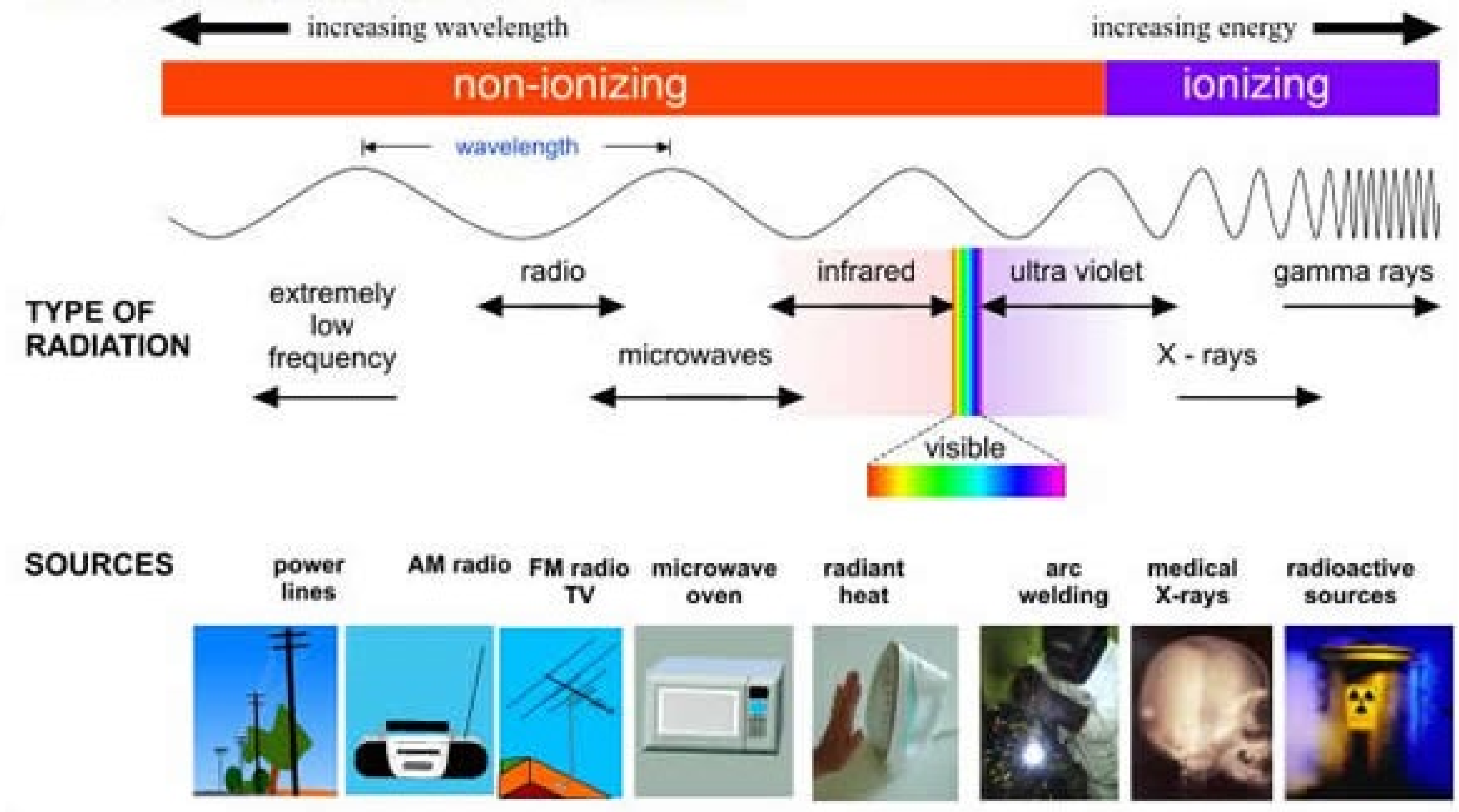
What is Radiation?

- When an atomic nucleus is unstable it emits something to get to its “ground state”.
- This “something” is called radiation
  - Particles: alpha, beta, neutrons, etc.
  - Photons (light): gamma rays, x rays*



* x-rays emanate from interactions involving electrons, either free or bound to an atom.

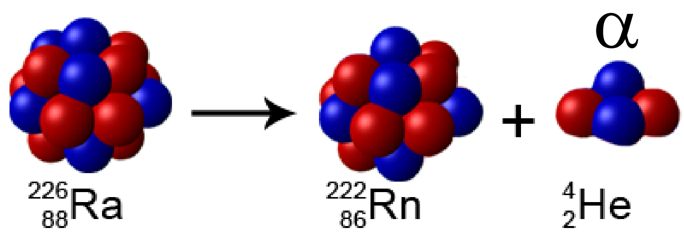
The Electromagnetic Spectrum



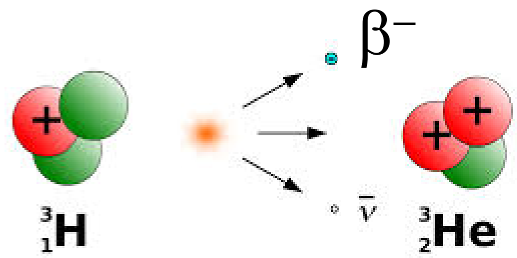
Ionizing Radiation can strip electrons from atoms and damage cells and components.

Examples of Radioactive Decay

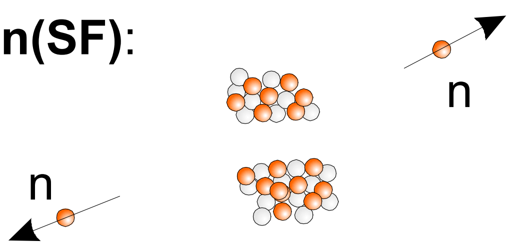
Alpha Decay:



Beta Decay:



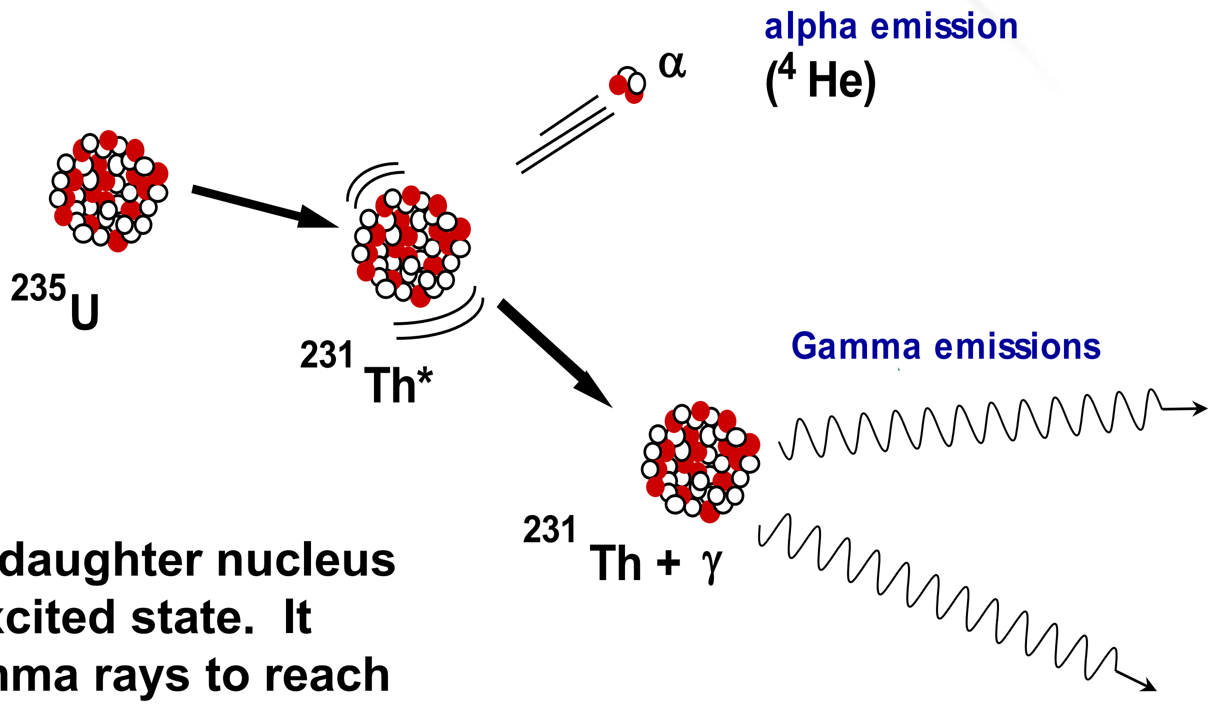
Spontaneous Fission(SF):



Gamma decay often follows one of these other decay modes

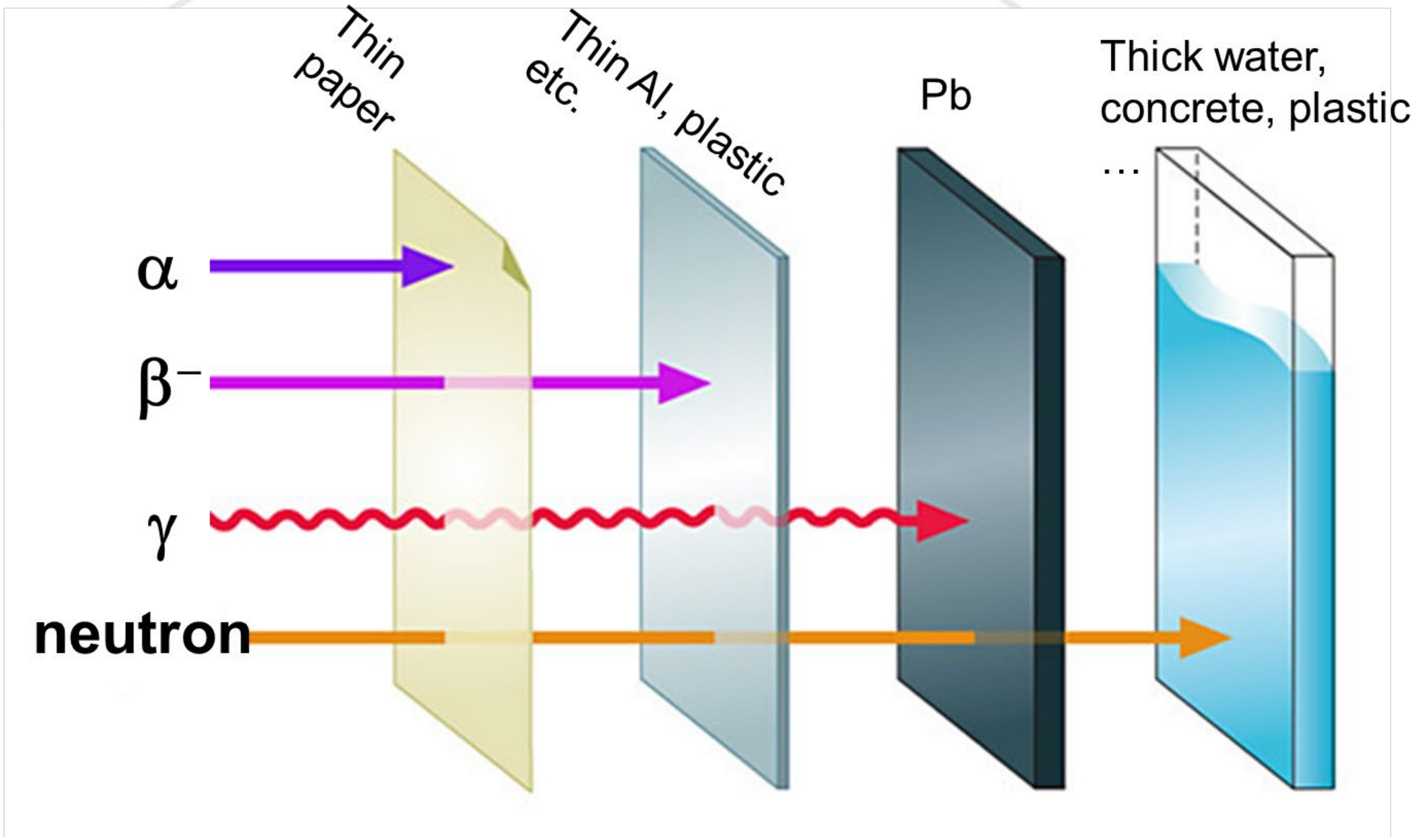
Note: These are all types of ionizing radiation.

Gamma Radiation



The ^{231}Th daughter nucleus is in an excited state. It emits gamma rays to reach the ground state.

How Penetrating is Radiation?



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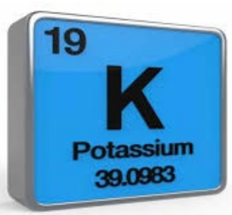
Measures of Radioactivity

- Activity
  - Disintegrations per unit time
  - Indicates how “strong” a source is
- Units
  - 1 Curie (Ci) = 3.7E10 disintegrations per second (dps)
  - 1 Becquerel (Bq) = 1 disintegrations per second (dps)

A 70-kg human has about 4 kBq of ^{40}K activity



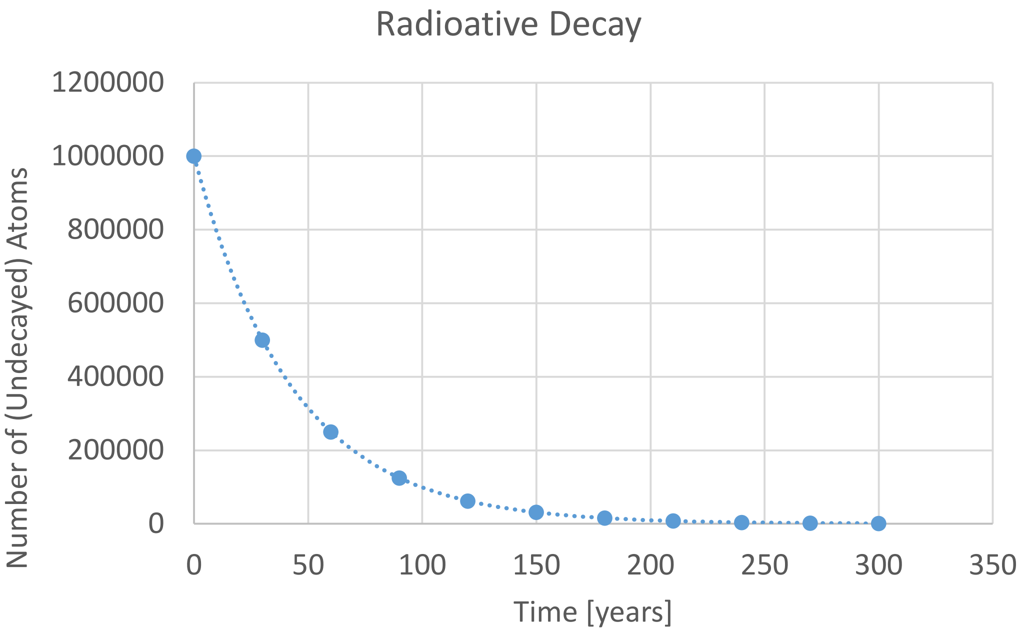
Radioactive Decay Law

$$N(t) = N_0 e^{-\lambda t}$$

# of atoms at time *t*

Initial # of atoms

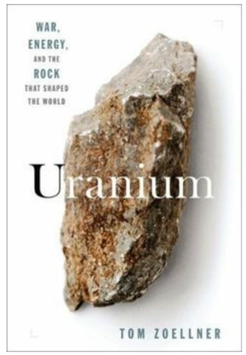
Decay constant = *ln*2 / $T_{1/2}$

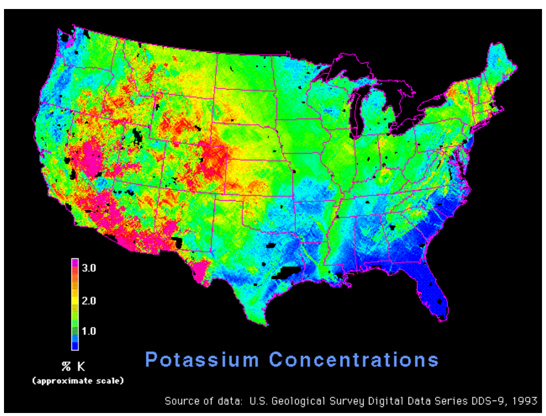


Half Life[y]	Initial Number of Atoms	
30	1.00E+06	
Time [y]	**N(t)**	**% of Initial**
0	1000000	100.0
30	500000	50.0
60	250000	25.0
90	125000	12.5
120	62500	6.3
150	31250	3.1
180	15625	1.6
210	7813	0.8
240	3906	0.4
270	1953	0.2
300	977	0.1

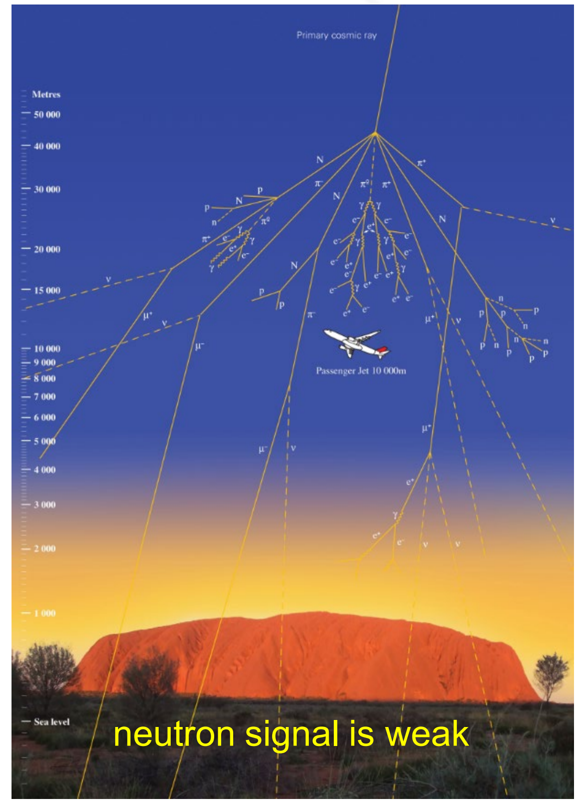
Natural Background Radiation

Gammas: From the Earth





Neutrons: From Space



Special Nuclear Material

- Special Nuclear Material (SNM):
  - Highly-Enriched Uranium (HEU): Key Nuclide is ^{235}U
  - Plutonium: Key Nuclide is ^{239}Pu
  - ^{237}Np
  - ^{233}U
  - Others but they are less common

- All of above listed nuclides are 'fissionable'. Of these, all <u>except</u> ^{237}Np are *fissile*.
- SNM is very dense in metal form and is composed of elements with high atomic numbers.
- Gram for gram SNM is not very radioactive compared to common sources like ^{137}Cs (Note: except ^{233}U items with high (ppm) ^{232}U concentrations).

General Signatures of SNM

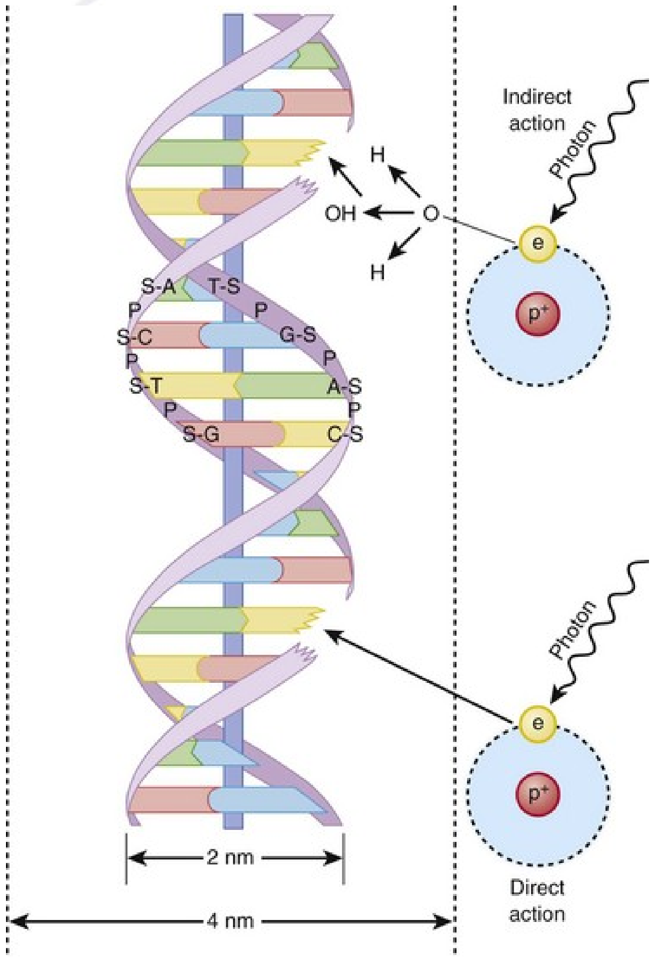
- HEU: gammas mainly at lower energies
- Plutonium:
  - Gammas from low to medium/high energy
  - Neutrons (60,000 n/s/kg for WGPu)
  - It can be warm or hot to the touch in sufficient quantity
- ^{237}Np: gammas mainly at medium energies
- ^{233}U: gammas
  - Direct gammas at medium energies
  - Most intense gammas from ^{232}U (at ppm concentrations) cover a wide range up to high energies

Low Energy: < ~250 keV
Medium Energy: ~250 – 1000 keV
High Energy: > ~1000 keV

Radiation Exposure and Dose

- Exposure
  - A measure of the ionization of air by photons
  - Units:
    - Roentgen (R)
    - Coulombs/kg
- Absorbed Dose
  - Energy deposited per unit mass in any object
  - Units:
    - Rad
    - 1 Gray (Gy) = 100 Rad

Radiation and the Human Body



When cells are exposed to ionizing radiation, radiochemical damage can occur either by “direct” or ”indirect” action.

Direct Action occurs when radiation ionizes a critical cell target (main concern is DNA).

Indirect Action occurs when ionizing radiation creates “free radicals” that react destructively with a critical cell target .

Equivalent Dose

- Used to assess the potential for biological damage from an absorbed dose

Equivalent dose (Sv or Rem)

$$D_{eq} = \sum_i A_i \times w_i$$

Absorbed dose for i^{th} radiation type (Gy or Rads)

Weighting (or "Quality") Factor for i^{th} radiation type

1 Sievert (Sv) = 100 Roentgen Equivalent Man (Rem)
1 mRem = 1/1000 Rem

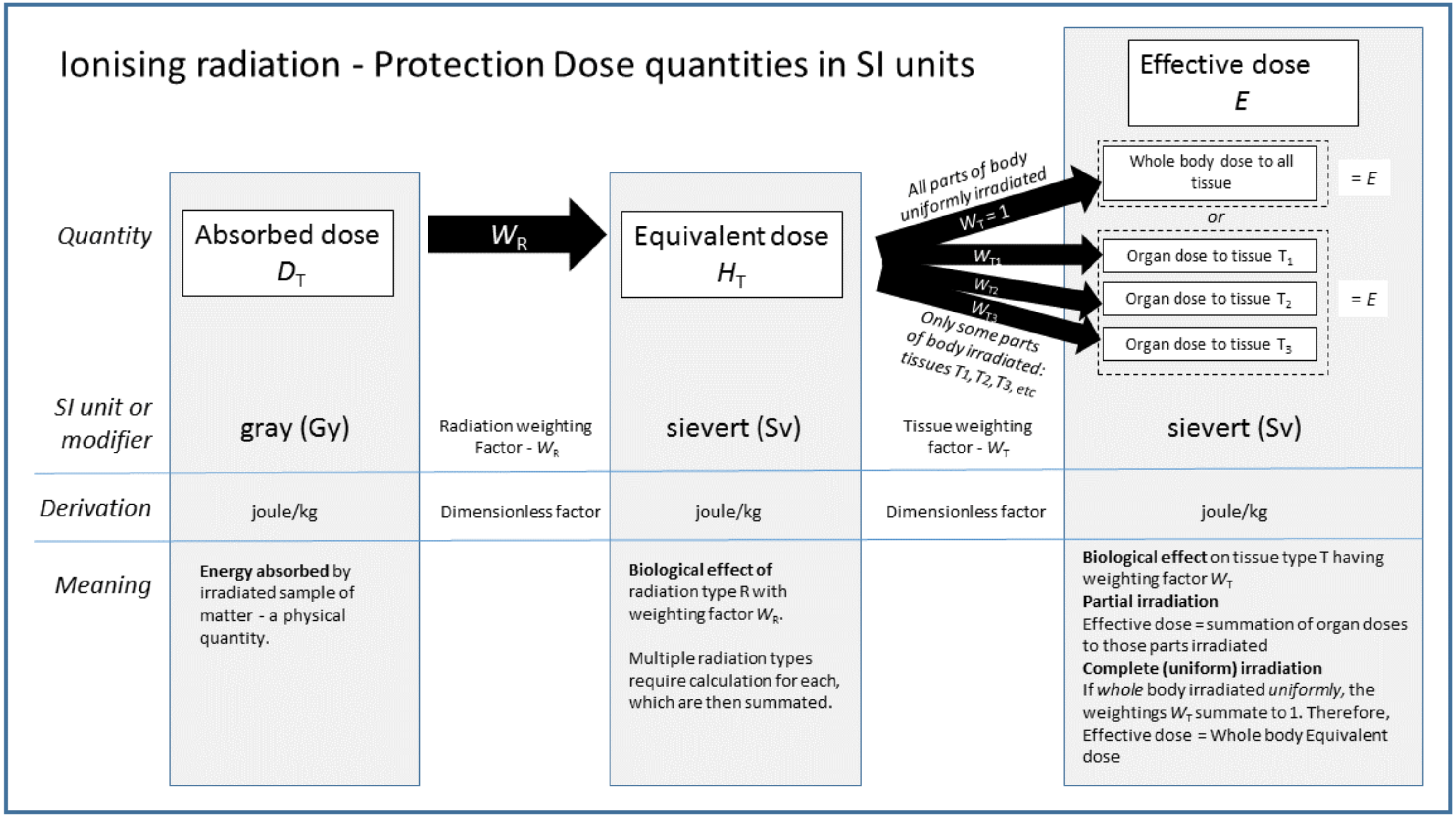
Equivalent Dose : Quality Factors

Radiation Type and Energy Range	Radiation Weighting Factor, W_R
X and γ rays, all energies	1
Electrons positrons and muons, all energies	1
Neutrons:	
< 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
Protons, (other than recoil protons) and energy > 2 MeV,	2-5
α particles, fission fragments, heavy nuclei	20

[ICRU 60, 1991]

Effective Dose Equivalent

Sum of equivalent doses to organs and tissues scaled by tissue weighting factors



External + Internal Dose

- From ingested or inhaled contamination
- Committed Dose Equivalent (CDE)
  - dose to some specific organ or tissue that will be received from an intake of radioactive material by an individual during the 50-year period following the intake.
- Committed Effective Dose Equivalent (CEDE)
  - sum of the products of the CDEs for each of the body organs or tissues multiplied by the weighting factors applicable to each of those organs or tissues
- Total Effective Dose Equivalent (TEDE)
  - Sum of external and internal (committed) effective dose equivalents

The Cookie Problem

- 4 radioactive cookies (equal activity, half lives)
  - Alpha
  - Beta
  - Gamma
  - Neutron
- Four choices: eat one, put one in your pocket, hold one in your hand, throw the other away

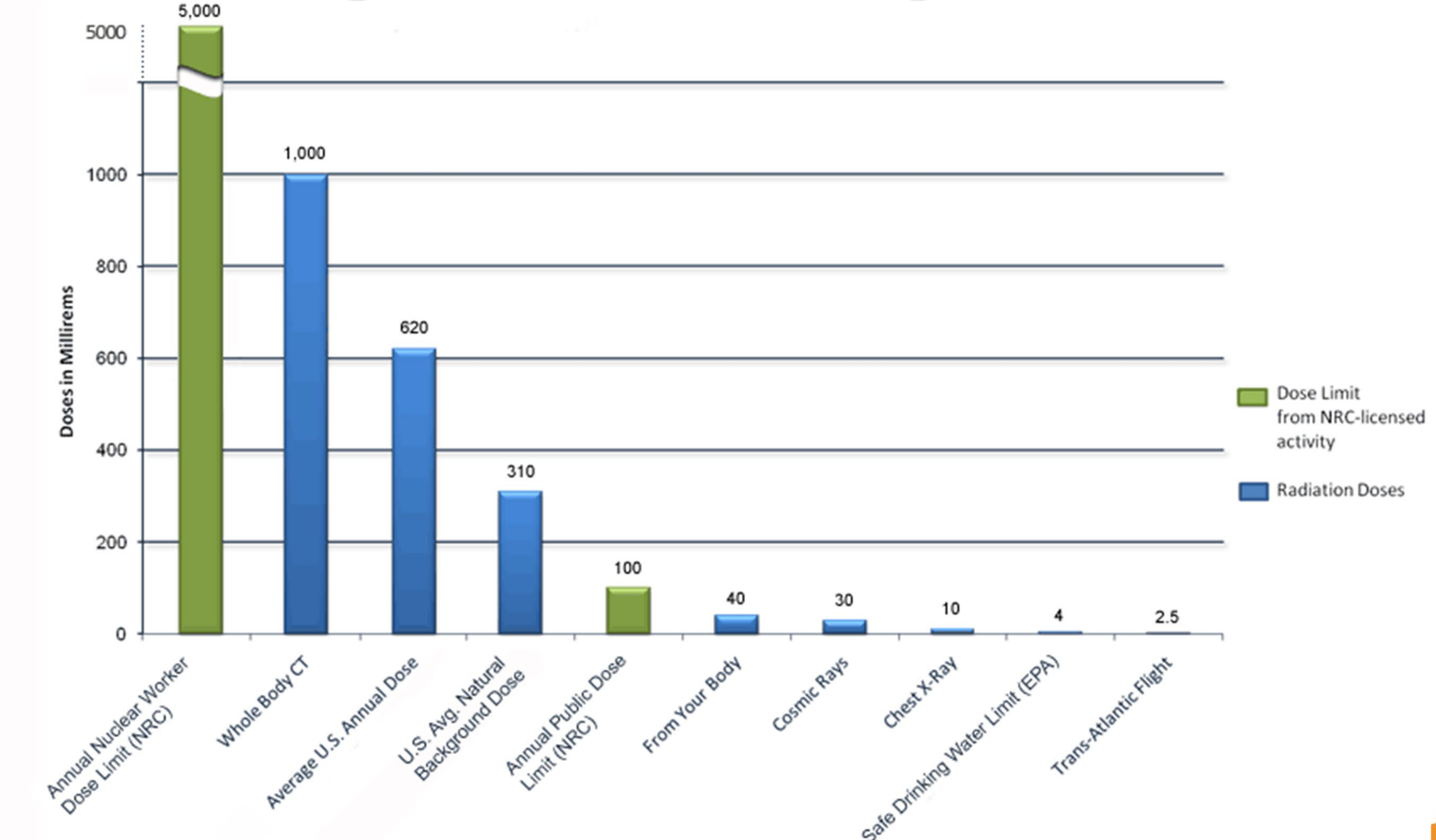
What do you do?

DOE Regulatory Limits

- 5 rem/yr CFR limit
- 2 rem/yr administrative control level
- 0.5 rem to developing fetus (0.2 ACL)
- For occupational exposures
- ALARA still required
- Emergency Response Exposure Limits
- – Higher limits & Volunteers

Note: we get ~ 1 mrem / day from the natural background and about 2 mrem / day from all sources.

Radiation Dose Examples



Overexposure Consequences

RADIATION DOSES Millisieverts (mSv)

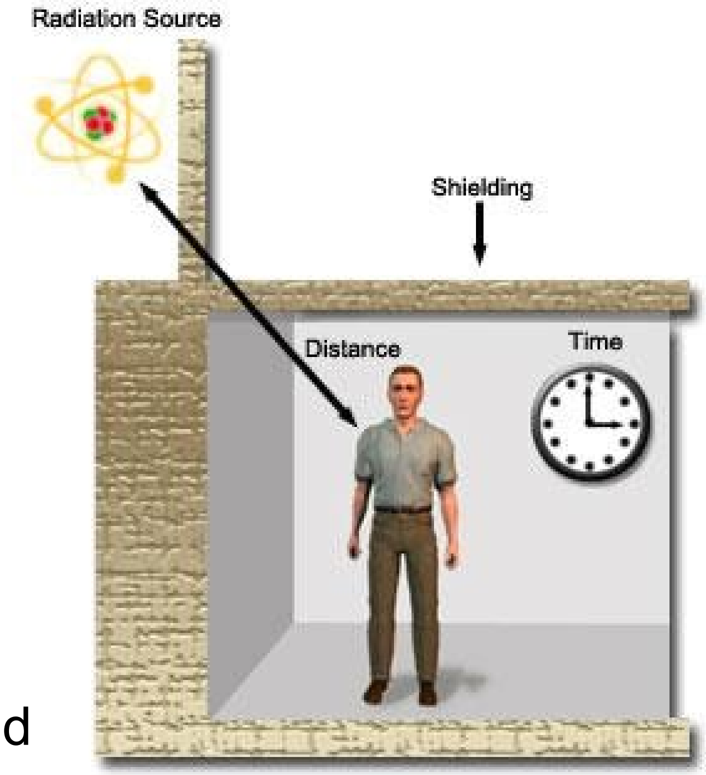
10,000	Acute radiation poisoning – death within weeks
6,000	Typical dose received by Chernobyl nuclear plant workers who died within one month of accident
3,000	Survival rate approximately 50 percent
2,200	Reading found near tanks used to store radioactive water at Fukushima plant, Sep 3, 2013
1,000	Causes radiation sickness and nausea, but not death. Likely to cause fatal cancer many years later in about 5 of every 100 persons exposed
700	Vomiting, hair loss within 2-3 weeks
500	Allowable short-term dose for emergency workers taking life-saving actions
400 per hour	Peak radiation level recorded inside Fukushima plant four days after accident
350 per lifetime	Exposure level used as criterion for relocating residents after Chernobyl accident
250	Allowable short-term dose for workers controlling 2011 Fukushima accident
100	Lowest level linked to increased cancer risk
20 per year	Average limit for nuclear industry workers
10	Full-body CT scan
2.4 per year	Person's typical exposure to background radiation
0.01	Dental x-ray

Sources: IAEA, World Nuclear Association

Localized Overexposure

ALARA

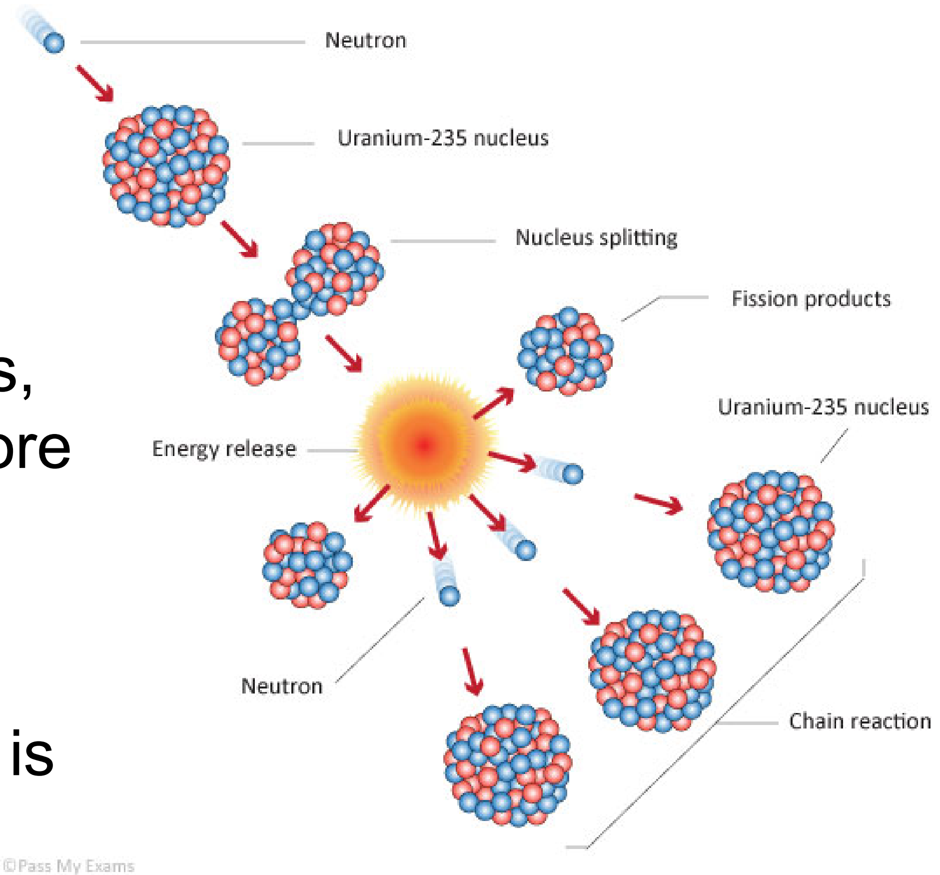
- As Low As Reasonably Achievable (ALARA)
- Time:
  - decrease time near source
- Distance:
  - increase distance from source
- Shielding:
  - increase shielding between you and the source



Nuclear Chain Reaction

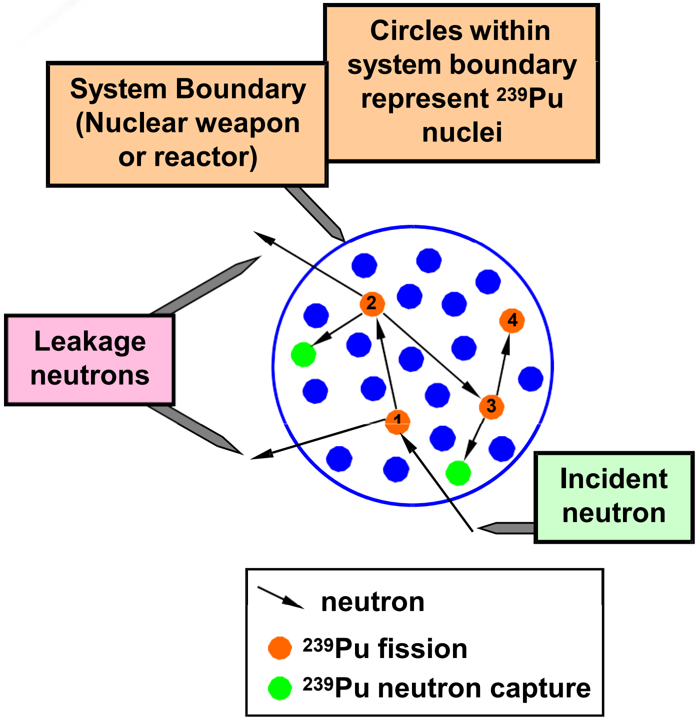
Chain Reaction: a neutron fissions a nucleus, which releases 1 or more neutrons, which subsequently split more nuclei, and so on …

Each time a fission occurs about ~200 MeV of energy is released.



Criticality

***Criticality*: measure of how the number of neutrons (and energy release) in the system (e.g., nuclear weapon or reactor) will change over time**



Change in Neutron Population (DN) = Neutrons Produced - Neutrons Lost

Production Mechanisms:
1) Fission reactions
2) Source
3) Other reactions e.g., (n,2n)

Loss Mechanisms:
1) Leakage
2) Neutron reactions e.g., (ng)

Criticality

$DN < 0$
Production < Loss

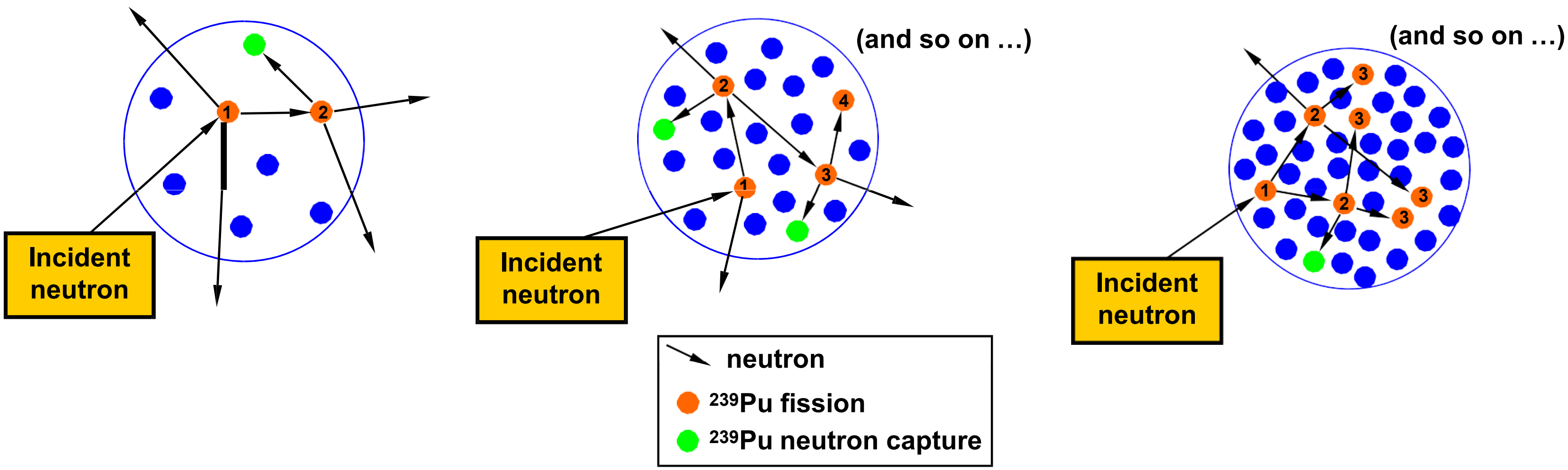
Subcritical system:
number of neutrons
(and energy release)
decreases with time

$DN = 0$
Production = Loss

Critical system:
number of neutrons
(and energy release)
constant with time

$DN > 0$
Production > Loss

Supercritical system:
number of neutrons
(and energy release)
increases with time



Factors Affecting Criticality

- ***Critical mass:*** **amount of material needed to form a "critical system," just sustaining a steady-state fission chain reaction (constant neutron population and energy production)**
  - Mass
  - Material
  - Density
  - Shape
  - Surrounding

Mass, Material, Density

- Material type: ^{239}Pu has a smaller critical mass than ^{235}U

Bare Sphere Critical Mass:

^{235}U
Density = 18.8 g/cm^3
Bare Sphere CM: 52 kg

^{239}Pu (α phase)
Density = 19.5 g/cm^3
Bare Sphere CM: 10.5 kg

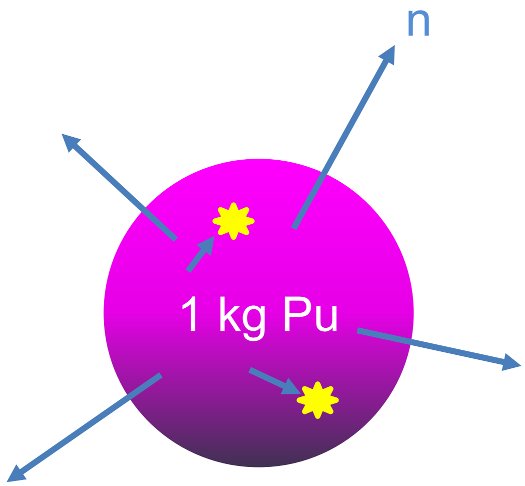
These numbers are for <u>pure</u> ^{235}U and <u>pure</u> ^{239}Pu at the quoted densities. As isotopic composition and density changes so does the critical mass.

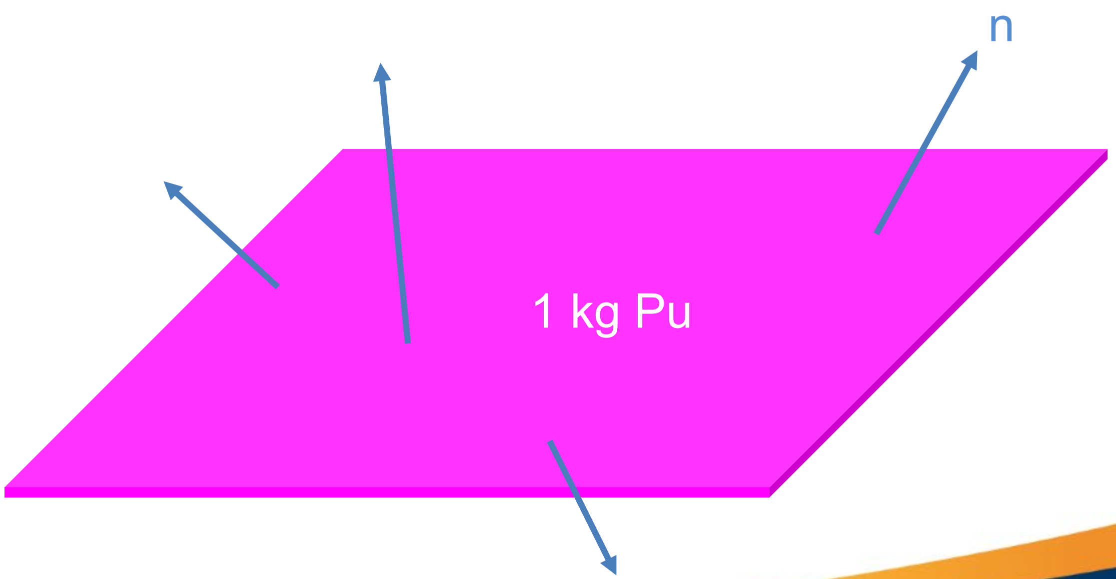
Shape & Neutron Multiplication

- How many neutrons do I produce for every "starter" neutron?

Neutrons from SF in the sphere have a better chance of inducing fission (producing more neutrons!) before they escape

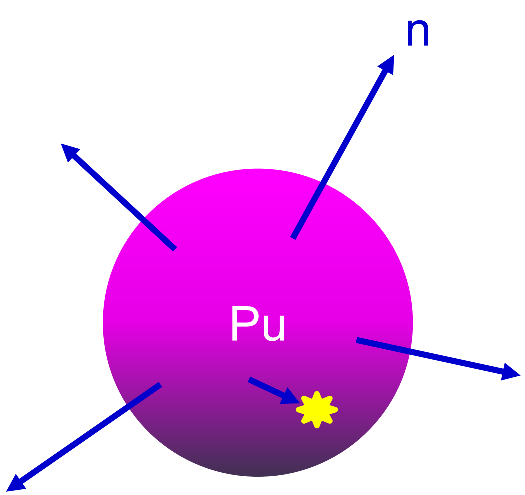
Neutrons from the flat plane more likely escape before inducing fission.

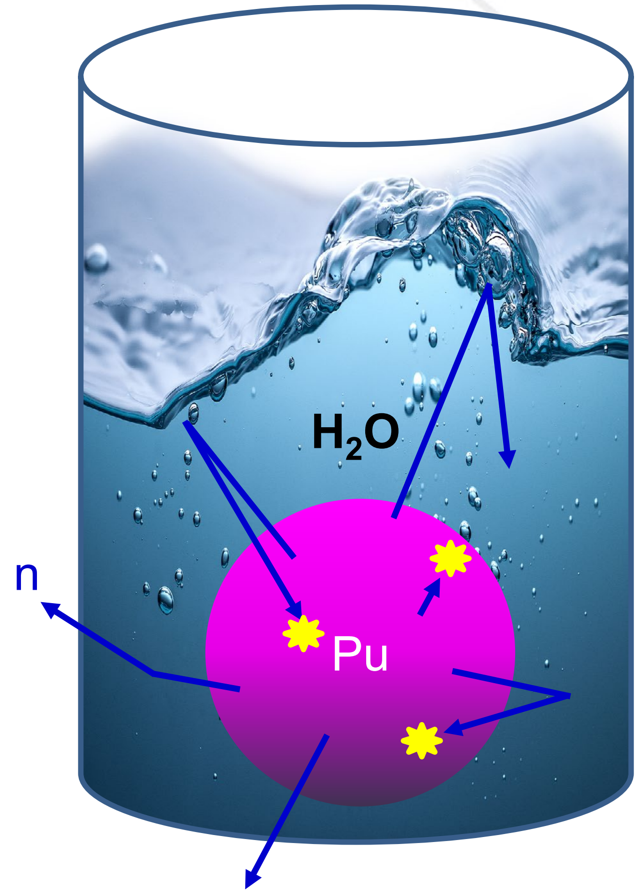




Reflection & Neutron Multiplication

Surrounding a neutron source with a reflecting material may send neutrons back into the material to induce more fissions.



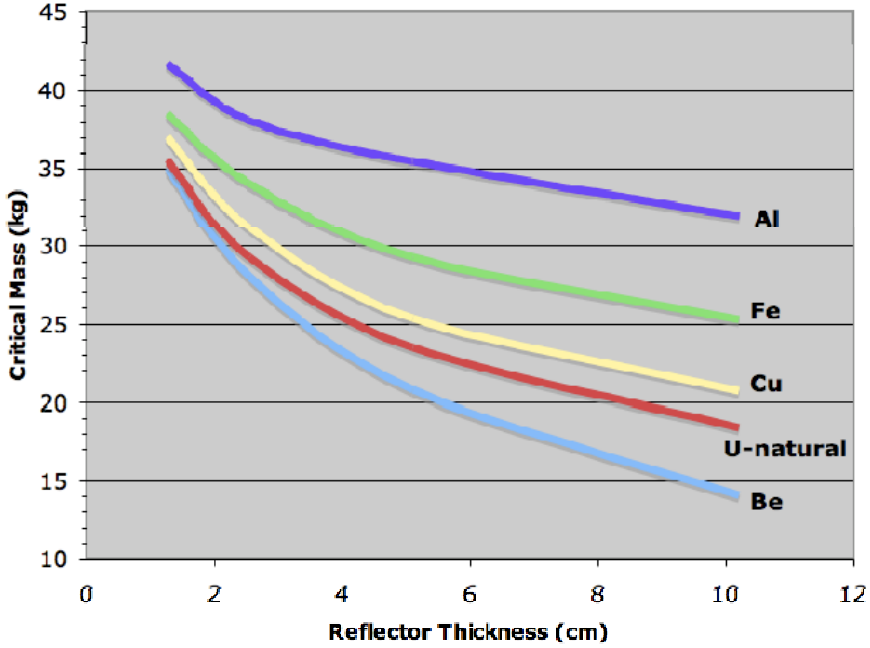


Induced fissions produce more neutrons (not shown) and so on.

Reflector Materials

- Reflectors reduce neutron leakage by scattering neutrons back into the fissioning material

Some reflectors are better than others



***Critical Dimensions of Systems Containing ^{235}U, ^{239}Pu, and ^{233}U*, Paxton and Pruvost, LA-10860-MS (1986)**

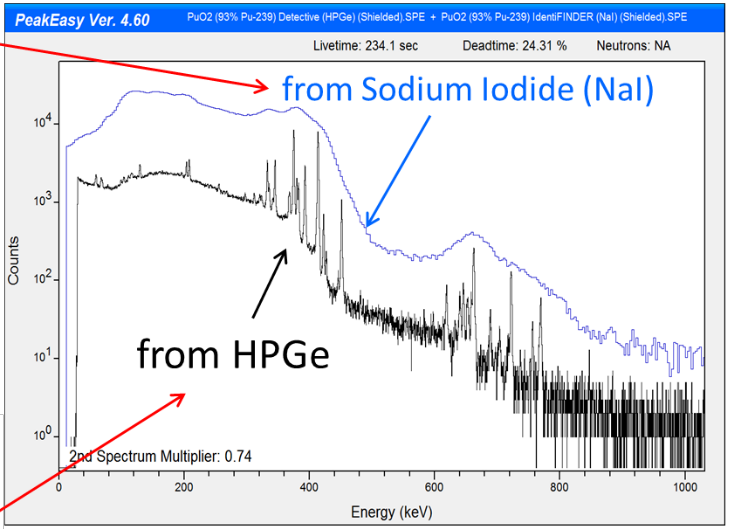
Critical Mass Examples

- Bare-sphere critical masses:
  - ^{235}U (18.8 g/cm^3): 52 kg
  - ^{239}Pu(α) (19.5 g/cm^3): 10.5 kg
  - ^{239}Pu(β) (15.7 g/cm^3): 16 kg
  - ^{233}U (18.4 g/cm^3): 15 kg
  - ^{237}Np (20.4 g/cm^3): 57 kg
- In solution at the right concentration these values are much lower (< ~1kg for Pu)
- Full-water reflection reduces these values by half

Radiation Detection

- We will talk about this in the laboratory demos!

A spectrum is like a fingerprint.



You get a better fingerprint with HPGe